An interpretation of the Voyager measurement of jovian electron density profiles

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The large vertical extent and diurnal variation in the electron density profile of Jupiter observed in radio occultation by Voyager 1 imply a homopause eddy diffusion coefficient of 1–3 $\times 10^5$ *cm*^{2} *s*$^{-1}$ *and an exospheric temperature of about 1,300 K.*

THE Voyager 1 radio science experiment (RSS) obtained electron density profiles for the daytime and night-time ionosphere of Jupiter by radio occultation observations on 5 March 1979[1]. The properties of the ionosphere were different from those obtained by the Pioneer 10 and 11 observations[2,3] in December 1973 and December 1974, in several important ways. (1) The vertical extent of the ionosphere in 1979 was about 6,000 km, compared to 3,500–4,000 km at the time of the Pioneer passages. (2) The peak in the daytime electron density occurred about 1,600 km above the reference pressure level (1 mbar) in 1979, compared to ~1,000 km above that level in 1973–74. (3) The scale height of the topside ionosphere in the daytime changes from about 590 km just above the peak to about 960 km at higher altitudes. In the night-time, there is a single topside scale height of 960 km corresponding to the high altitude daytime scale height. (4) Finally, the maximum electron density is a factor of 10 lower on the nightside than it is on the dayside. In the case of the Pioneer observations, only small variations were observed between daytime and night-time ionospheric profiles, and very small differences were evident as a function of latitude (20° N, 26° N, 58° N, and 79° S)[3]. The Pioneer 10 and 11 encounters with Jupiter occurred near solar minimum, while the Voyager 1 encounter was near the solar maximum. Here we attempt to account for the differences between the Pioneer and Voyager observations on the basis of solar cycle changes in solar flux, drastic decrease in the eddy diffusion coefficient in the upper atmosphere and a large increase in the exospheric temperature of Jupiter.

Atreya and Donahue[4] succeeded in accounting for the principal features in the Pioneer 10 and 11 ionospheric profiles by assuming a temperature of 1,000 K for the upper atmosphere and invoking radiative recombination of H^+ as the dominant ion loss mechanism in the principal ionospheric layer. Here we argue, first, that the temperature has increased to 1,300 K in 1979. This neutral temperature corresponds to the plasma scale height of 960 km which was measured at 3,500 km above the reference level on the dayside and at 2,300 km on the nightside. A lower temperature (1,100 K) was quoted by Eshleman *et al.*[1] This was the consequence of using the plasma scale height at 6,000 km. (G. F. Lindal, personal communication). However, photochemical time constants are small compared to diffusion times only below about 3,500 km, and, hence, we have chosen to calculate the temperatures at lower altitudes. Nagy *et al.*[5] have shown that approximate thermal equilibrium between the plasma and neutral gas occurs at this altitude. The difference between neutral, electron and ion temperature should be at most a few hundred degrees and has only a small effect on our results.

We have varied the eddy diffusion coefficient at the homopause from 3×10^7 cm^2 s^{-1} which was appropriate for Pioneer 10 and 11 conditions[4] to 8×10^4 cm^2 s^{-1} in order to ascertain the effect of a change in that atmospheric parameter on the ion density profiles.

We have also taken into account the variation with temperature of rate constants. The rate constant for radiative recombination of H^+ and electrons varies with electron temperature[6,7] between $T_e^{-0.5}$ and $T_e^{-0.75}$. A reaction discussed by McElroy[8]

$$H^+ + H_2(v' \geq 4) \rightarrow H_2^+ + H \quad (1)$$

becomes much more important at Voyager temperatures than those of Pioneer 10 and 11. Followed by

$$H_2^+ + H_2 \rightarrow H_3^+ + H \quad (2)$$

$$H_3^+ + e \rightarrow H_2 + H \quad (3)$$

Reaction 1 can be a very significant loss process for H^+ ions in the high temperature conditions encountered by Voyager.

Finally, extreme UV solar flux values appropriate to the conditions of the Voyager encounter were taken from those measured by Hinteregger (personal communication).

We have found that it is possible to reproduce the measured electron density profiles by using a model atmosphere appropriate to an exospheric temperature of 1,300 K with temperature varying above the homopause as in our previous calculations[4] and with an eddy diffusion coefficient K of $(1–3)\times 10^5$ cm^2 s^{-1} at the homopause. K varies with altitude inversely as the square root of the atmospheric number density above the tropopause. Its value at the tropopause was adjusted until an electron density profile matching the observed one was obtained. For example, in a model in which the value of the H_2 density at the homopause was 7×10^{13} cm^{-3} and K at that altitude was 1.5×10^5 cm^2 s^{-1}, the daytime maximum electron density of 2×10^5 cm^{-3} occurred where the H_2 density was 3×10^{11} cm^{-3}, 1,500 km above the 1-mbar level. (The observed peak was at 1,600 km.) The hydrogen density at the ionospheric maximum is somewhat higher than it was for the conditions of the Pioneer encounters[4] when the thermosphere was cooler and the solar flux was weaker. Given the present state of uncertainty in measured altitudes and plasma profiles, it is probably safe to take K as lying somewhere between 1 and 3×10^5 cm^2 s^{-1} at the homopause.

The rate of ionisation during the daytime is 26 protons cm^{-3} s^{-1} at the maximum. This is a full order of magnitude above the rate required to account for the ionosphere observed by the Pioneers. It is partly the consequence of the 2.5-fold increase in ionising solar flux that has occurred since the last solar minimum (H. E. Hinteregger, personal communication). It is also a result of the fact that an increase in atomic hydrogen column abundance in the upper atmosphere of Jupiter by a factor of 100 since 1973–74 is implied by the very large enhancement of jovian Lyα radiation detected by the UVS[9] and IUE (H. W. Moos and S.K.A. unpublished) observations at the time of Voyager encounter.

The time constant for loss of H^+ by radiative recombination is substantially greater than the length of a jovian night. This circumstance led to the small diurnal variations observed by Pioneers 10 and 11 [4]. We propose that the diurnal variation now

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observed leading to the tenfold enhancement in the maximum electron density, and the dual topside scale height during the day is a consequence of the enhanced importance of reaction (1) when the temperature in the upper atmosphere is 1,300 K in place of 850–1,000 K. In order to reproduce the observed diurnal variation, the loss frequency for H^+ in charge exchange with H_2 should be 1.3×10^{-4} s^{-1}, leading to an overall rate constant for reaction (1) of 4.3×10^{-16} cm^3 s^{-1}. Reaction (1) is endothermic in the ground vibrational state by 1.8 eV for H^+ at 300 K[10]. The rate constant for H_2 excited to the fourth vibrational level and higher at a temperature of 1,300 K would have to be 4×10^{-9} cm^3 s^{-1} to produce the required overall loss rate. This value would be reduced by about a factor of two if we take into account the high velocity of the H^+ ions at 1,300 K. Because of the rapid variation of the Boltzmann factor with temperature, a small increase in vibrational temperature would also lead to a sizeable relaxation in the value required for this rate constant. On the other hand, if the temperature should be 850 K as it apparently was during the Pioneer 10 and 11 observations, the rate constant for the reaction between H^+ and H_2 excited levels higher than $v = 4$ would have to be of the order of 10^{-5} cm^3 s^{-1} to produce a similar reduction in ion density.

The photochemical time constants are short compared with a jovian day up to an altitude where the dayside electron density is about 2×10^4 cm^{-3}. Hence, after sunset the electron density near the daytime peak will rapidly decay. The night-time ionospheric maximum will attain a density of $\sim10^4$ cm^{-3} and a single topside scale height corresponding to the upper part of the daytime profile. The nightside ionosphere is the dayside ionosphere with its low altitude bulge dissolved.

The ionosphere observed by Voyager 1 seems to imply the existence of a jovian exospheric temperature at 1,300 K and an eddy diffusion coefficient between 1 and 3×10^5 cm^2 s^{-1} at the homopause. This high temperature and low value of K compared with Pioneer conditions are also implied by the great enhancement in Lyα radiation observed by the Voyager UVS, and IUE, and the fact that the UVS failed to detect the He 584 Å radiation from the jovian disk. If the volume mixing ratio of He is 0.11 as reported by the IR spectroscopy and radiometry investigation[11], the failure of the helium resonance radiation to be observed by the UVS implies the presence of a large amount of hydrogen above the homopause and a value for K near the homopause of the order of 10^5 cm^2 s^{-1}. Although the rate constant we have calculated for reaction (1) seems reasonable, it will be highly desirable to measure it in the laboratory in jovian conditions.

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Plasma wave turbulence at Jupiter's bow shock

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The first measurements of the wave–particle interactions of Jupiter's bow shock are reported, and some of the wave phenomena detected during the inbound passage are discussed.

THE characteristics of a planetary bow shock are important because the plasma that impacts the magnetosphere of a planet represents solar wind that has been drastically modified by the shock process. Plasma instabilities that develop at a shock front are associated with significant acceleration processes that yield non-maxwellian distributions in the downstream magnetosheath as well as significant fluxes of suprathermal ions and electrons in the upstream region. The Voyager 1 plasma wave investigation has provided the first opportunity to study directly the wave–particle interactions of an outer planet bow shock. Here we discuss in detail some of the wave phenomena detected during the inbound passage.

Measurements

The initial report on the Voyager wave data[1] contains a brief summary of the inbound shock measurements with a display of the 16-channel spectrum analyser data from the first bow shock crossing (detected at 14.34 spacecraft time, 28 February 1979, when the spacecraft was at a range of 85 R_J). Figure 1 shows a corresponding plot of the 16-channel wave data for the third shock crossing of 12.27 UT on 1 March, detected when Voyager 1 was at a range of 72 R_J. We focus attention here on this third inbound crossing for which we have the most comprehensive data records.

Before 12.27, Fig. 1 shows that electrons produced steady oscillations in the 5.62 kHz channel, corresponding to an upstream density of $\sim$0.4 electrons cm^{-3}. The high frequency upstream wave amplitudes were almost an order of magnitude higher than those detected in the corresponding region the day before, but in the low-frequency channels where ion acoustic waves and whistlers are generally detected, the 1 March bow shock exhibited a noteworthy absence of precursor wave activity. (The sporadic signals in the 100-Hz channel are interference tones from the stepper motor of the low energy charged particle instrument.) This third shock crossing was characterised by the detection of intense broadbanded noise enhancements in a well defined time interval with duration of the order of 1 min. Analyses of collisionless shock structures[2] suggest that the minimum shock thickness for a laminar structure should be of the order of $\delta_i = c/(2\pi f_p^i)$ where c is the speed of light, f_p^e is the electron plasma frequency ($f_p^e = 9\sqrt{N_e}$ kHz where N_e is the electron density in cm^{-3}) and $f_p^i = f_p^e/43$ (for protons). For our

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